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Durable Highway Structures – Recent Developments in Ontario

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DURABLE HIGHWAY STRUCTURES - RECENT DEVELOPMENTS IN ONTARIO

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ABSTRACT

The deterioration of highway structures in North America in areas where deicing salts are used, and the resulting large expenditures required for structure rehabilitation or replacement, has led to a search for new materials and design and construction techniques which will give assurance of improved long-term durability in new construction.

The paper describes recent developments in Ontario towards the goal of maintenance free structures including changes in design and construction details and the adoption of new materials technology. Various methods of achieving positive protection for superstructure and substructure elements are presented including warrants for the use of epoxy coated reinforcing bars, the use of increased concrete cover to steel, the adoption of higher qualities of concrete and an increase in the minimum thickness of the bridge decks and barrier walls. The additional cost of providing positive protection to structures is discussed.

It is noted that the quality of a structure depends largely on workmanship in construction and the importance of effective quality assurance inspection, testing procedures and acceptance criteria is emphasized.

INTRODUCTION

The near astronomical funding requirements [1] estimated by some authorities in North America as necessary for the replacement and rehabilitation of highway structures leaves no doubt that the design, construction and maintenance standards used in the 50's, the 60's and the 70's were inadequate in terms of producing bridges with long life and low maintenance costs. Deterioration is widespread, and in many cases significant. Examples of deterioration are shown in Figure 1.

One major problem is that salt solutions from winter maintenance operations penetrate various elements of the structure and initiate corrosion of the steel reinforcing bars. This in turn causes cracking and rupturing of the concrete and spalling of the concrete surface. In addition, some older bridges built to lower standards of quality than modern structures and without the benefits of air entrainment in the concrete and efficient water-proofing membranes on the deck slab, suffer a more deep seated distress as the salt laden, saturated concrete progressively disintegrates under freeze thaw action.

A recent paper [2] concludes that the total cost of bridge deck rehabilitation for the 2700 bridges on the MTC system in Ontario over the next 10 years is approximately $200 million (1981 funds). New York State DOT reports [3] that structures are deteriorating faster than they are being rehabilitated and points out the need for a significant increase in maintenance expenditures, to avoid a condition defined as "projected failure of the highway network".

This attention to the condition and maintenance of structures is not new. Almost 20 years ago an investigation [4] revealed that a very high proportion of bridge decks in Ontario were being attacked by frost action and waterborne salt resulting in deterioration to the concrete slab.

Since Ontario, like many other agencies, has changed many of its standards and policies for structure construction during the last two decades, the poor performance of bridges of comparatively recent vintage, indicates the difficulty in satisfying durability requirements for highway structures.

The purpose of this report is to review developments and policies adopted by Ontario in recent years with the goal of significantly improving the long term durability of new construction. A key element in Ministry strategy is the use of epoxy coated reinforcing bars in bridge decks and some substructure elements to prevent corrosion induced damage to the structure.

CONSTRUCTION QUALITY AND MATERIAL PROPERTIES

The environment of a highway structure in Ontario, particularly the bridge deck, represents one of the worst imaginable exposure conditions for concrete. Engineers have known since the principles of concrete technology were first postulated that a vertical surface is more durable than a horizontal surface, that alternate wetting and drying is a more severe exposure than total submersion, and that freezing and thawing is more damaging than constant freezing. It was also recognized that in a marine environment a clear concrete cover of at least 75 mm was necessary to protect the steel against corrosion by salt water. Despite the fact that many bridge decks in North America are subjected to frequent applications of deicing salts on a horizontal surface, alternate wetting and drying, and freezing and thawing, until recently the specified concrete cover to the top steel was typically 38 mm. The specified cover in other concrete elements, such as piers and abutments, has also proven to be inadequate.

The Ministry like many other highway agencies uses large quantities of road salt (sodium chloride) to clear ice and snow from pavements during the winter months. In the winter of 1981/82 approximately half a million tonnes of salt was used on the MTC network.

Bridge decks also are subjected to severe temperature gradients and high live-load stresses, including fatigue and impact. They contain a congestion of reinforcement, cables and anchorages, making the use of highly workable concrete essential. Because of finishing and bleeding, the worst quality of concrete in the deck is at the surface. Clearly the challenge of providing satisfactory long term durability to highway structures is a formidable one.

The durability of reinforced and prestressed concrete in a corrosive environment is determined by careful design details, high quality materials and good construction practices. Concrete members exposed to chlorides in service and subjected to intermittent wetting are particularly vulnerable to corrosion damage. The degree of protection provided by the concrete against corrosion is a function of the depth of cover to the reinforcing steel and the permeability of the concrete [5, 6]. Concrete permeability depends upon numerous factors though the most important are water-cement ratio, degree of consolidation and adequacy of curing. It should be noted that although resistance to penetration by chloride ions is substantially improved as the concrete permeability decreases, it is not possible to upgrade the quality of concrete sufficiently using conventional construction procedures to render it impermeable.

The combined effects of water-cement ratio and depth of cover for a properly consolidated concrete are shown in Figure 2. The figure illustrates the number of daily applications of sodium chloride to specimens in an outdoor exposure plot before the potential of the reinforcing steel was more negative than -0.35 v to the copper/copper sulphate half cell, which is considered to be the potential at which there is a 90% probability that the steel is corroding. Thus in a concrete with a water-cement ratio of 0.40, 40 mm of cover was found sufficient to prevent corrosion

of the steel for 800 applications of salt [6]. Equivalent protection was afforded by 70 mm of concrete with a water-cement ratio of 0.50, or 90 mm of 0.60 water-cement ratio concrete. The number of years of service which this represents in actual structures subjected to deicing salts has not been established. However, corrosion will begin quickly on reinforcement embedded in poor quality concrete. It has been shown that sufficient chloride to initiate corrosion had penetrated to reinforcement embedded in concrete having a water-cement ratio of 0.50 and a slump of 80 mm in only seven daily applications of salt when the cover was 25 mm [7].

It is on the basis of the work shown in Figure 2 that the ACI Committee report "Guide to Durable Concrete" [5] recommended a minimum cover of 50 mm for bridge decks if the water-cement ratio is 0.40 and 65 mm if the water-cement ratio is 0.45. It is important to note that in the corrosive environment to which highway structures are exposed, protection against corrosion will often require a lower water-cement ratio of the concrete than is necessary to achieve the design strength of the concrete. Furthermore the overall member thickness may be dictated by the required covers and an allowance for placing tolerances rather than strength considerations.

Such is the case for thin slab bridge decks where the Ministry has recently increased the minimum deck thickness to 225 mm. A survey undertaken in the fall of 1976 to determine the extent of compliance with the specification requirement at that time of 63.5 ± 12.5 mm for the top mat of steel in deck slabs found a wide variation in cover measurements [8]. The results given in Table 1 show the compliance with the specification varied between 18 and 100%. On three structures stirrups were bent in the field to accommodate the required cover and in one structure additional payments were made to the contractor to securely tie the steel to the main beams. The standard deviation of all readings was 12.5 mm. These findings caused considerable concern and steps were taken to tighten the requirements for placing the steel.

The layout of the reinforcement and the placing tolerances for thin slab decks are illustrated in Figure 3.

The concrete cover standard deviation (σ) of the top mat of steel placed by a diligent contractor has been found to be 10 mm from measurements in Ontario and elsewhere [9]. The acceptance criterion has been defined as not more than 2.5 percent of the measurements shall be less than the specified minimum cover. Most studies have shown that the cover to the steel follows a normal distribution. The acceptance criterion then corresponds to a band width of $1.96\,\sigma$, which means that 95 percent of the bars will be within the range of the average cover $\pm\ 1.96\,\sigma$. The minimum covers specified by the Ontario Highway Bridge Design Code [10] are 50 mm to the top mat and 30 mm to the bottom mat. It has been assumed that the tolerance for placing the bottom steel is ± 10 mm and that 20 M bars will be used. Where 15 M bars are used, this will result in a slight increase in space between the mats which must be 25 mm apart to allow for the use of 19 mm concrete aggregate.

As shown in Figure 3 (a), if average covers were maintained, the minimum required deck thickness would be 215 mm. However if maximum clearances to the top and bottom steel occur simultaneously, the minimum required deck thickness is 225 mm, even when the longitudinal bars are staggered to maintain the clearance between the mats. Since no allowance has been made for the variations of the concrete slab thickness, which could be ± 10 mm, it is thought reasonable to provide for the minimum deck thickness of 225 mm required for the case illustrated in Figure 3 (b).

If the reinforcing steel is given a stable, impermeable coating, it is apparent that the steel will be isolated and prevented from contact with water, salt solutions and oxygen. Thus corrosion is prevented.

Consequently a key element in the Ministry policies and procedures aimed at long life and low maintenance costs in new bridge construction is the use of epoxy coated bars (Figure 4) near the faces of bridge components exposed to salt. Fusion bonded epoxy coatings were identified as suitable non-metallic coatings for reinforcing steel in screening tests carried out at the National Bureau of Standards in the early 1970's [11]. The process of coating reinforcement developed from the application of epoxy coatings to small diameter pipe but can now be considered a coating technology in its own right. Plants have been constructed in which the complete process of cleaning, heating, coating and curing is carried out as a continuous process on a single production line. The bars are blast cleaned to a near white finish and then heated, often by induction coils, to the temperature required for the application of the epoxy powder, usually 200 to 230°C. The bar then passes through an electrostatic spray which applies the charged dry powder to the heated bar. Damage to the coating during the short gel time is prevented and the coated bar is water cooled as it advances along the line. A holiday detector is located at the end of the line to check the bar for defects. A typical coating thickness is 7 ± 2 mils (0.18 ± 0.05 mm) and it is a requirement in Ontario that the colour of the coating provides a sharp contrast with the appearance of rusted steel.

Initially an attempt was made to obtain a coating completely free from defects but the touch-up work required to do this was tedious and almost prohibitively expensive. Tests were undertaken to determine the amount of damage in transportation and handling which can be tolerated. Epoxy coated bars in which major nicks and cuts were deliberately made in the coating showed no failure after 35 months of exposure to very severe corrosive conditions [12].

This work lessened the concern that a small exposed area of steel would be susceptible to intense corrosion activity and enabled specifications for patching to be relaxed. Instead, increased emphasis has been placed on proper fabrication and handling procedures to prevent damage. Concern was again raised for the susceptibility of damaged coated bars to corrosion by a number of U.S. highway agencies where epoxy coated bars are used in exposed concrete decks. There is a potential problem that where only the top mat of steel is coated, and damage occurs, the bottom mat of steel may act as a large cathode to drive macrocell corrosion at the bar

defect which becomes an anode. Tests were again undertaken to investigate the coupling effect and by taking rate of corrosion measurements the life of epoxy coated bars with differing degrees of damage was calculated with respect to uncoated bars which were assigned a life of five years. The results are given in Table 2.

The data indicates that electrical coupling of an epoxy coated top mat and an uncoated bottom mat can induce accelerated corrosion [13]. However, it appears to be of practical concern only when the total visibly bare area exceeds 0.24 percent. It must also be remembered that the concrete in the above tests was exposed to chlorides from the time of construction. Where a waterproofing membrane is used, the effectiveness of the epoxy coating is extended considerably because of the amount of time required for chlorides to penetrate the membrane and permeate the concrete to the level of the steel.

MTC APPROACH TO THE PROBLEM

By the early 1970's bridge deck deterioration had been recognized as a serious problem in Ontario though there were diverse opinions concerning what action the Ministry should take. A research study was initiated in 1975 to examine the many protective systems which were recommended for the prevention of deterioration in structures. A state-of-the-art report was produced [14] that recommended the practice of waterproofing bridge decks continue but that the feasibility of two stage deck construction be investigated. Low slump concrete, latex-modified concrete and internally sealed concrete were identified as promising overlay systems for the second stage of construction.

Faced with the task of investigating and implementing new technology in the shortest time possible, the Ministry's senior management assigned responsibility for the bridge deck programme to a task force representing the various engineering sections. During 1976 and 1977 demonstration projects were undertaken for the construction of concrete overlays on 22 bridges. Construction activities, cost and performance were monitored closely [8,15]. The development of a cathodic protection system for bridge decks which had begun in 1974 was continued and by 1977, six bridges were cathodically protected [16,17]. Simultaneously, laboratory studies were undertaken, the performance and costs of epoxy coated reinforcing steel were investigated through research into construction practices in the United States and several projects involving the use of two stage construction on new decks and the repair of deteriorated bridges were carried out.

Following this two year period of intense activity in bridge deck projects, the Ministry had gained direct experience in concrete overlays, fibre reinforced composites, cathodic protection and waterproofing membranes, and had acquired information on the cost and performance of epoxy coated and galvanized reinforcing steel. Specifications for all these protective systems had either been developed or were available and the suitability of each for use in new construction was assessed. Fibre-reinforced composites were only considered for crack-bridging applications in deck rehabilitation and internally sealed concrete was found to

be not practical. Galvanized reinforcing steel was rejected because of conflicting performance data. A financial analysis of the remaining systems was made by taking the actual costs of a typical three span, thin slab deck on prestressed concrete beams built in 1976 and determining the unit costs for various new construction strategies. Bridge deck costs were developed for the structure as built and for the deck if it had been designed to take advantage of the reduced steel percentage permitted by the Ontario Highway Bridge Design Code (10) which was being written at that time. The costs for the concrete overlays were taken from the demonstration projects and the costs of epoxy coated bars were based on U.S. data.

The initial construction costs are given in Table 3. This shows that for the typical thin slab structure chosen, the deck slab represented 28.8% of the total cost of the structure and the protective system, consisting of a rubberized asphalt waterproofing membrane, protection board and 75 mm of hot mix, a further 3.6%. Table 4 gives the total cost of the structure, expressed in unit cost of deck area, for various alternatives. The maintenance costs of strategies using a waterproofing membrane were based on removal and replacement every 15 years. Lower maintenance costs were assumed for concrete overlays. As expected, the provision of additional protection to the structure resulted in an increase in costs. The use of epoxy coated bars with a conventional waterproofing system was the least expensive alternative and increased the cost of the structure by 2.1% as built and by 1.8% if the quantity of deck reinforcement were reduced. In addition to having a higher initial cost, concrete overlays were found to have the disadvantage in new construction of significantly reducing the construction season because they cannot be placed at temperatures less than 5°C. Conversely, epoxy coated bars offered the following advantages:

i) Bridges already designed did not have to be redesigned because dead load is unchanged.

ii) Few changes were required in construction procedures.

iii) Proven materials were available.

The task force recommendation that epoxy coated bars be used in the top mat of bridge decks and in curbs and barrier walls was presented to the Ministry's senior management in April 1978. The recommendation was approved for implementation in all contracts awarded after November 1, 1978. In practice this meant that most structures built during 1979 would incorporate epoxy coated rebars. Where feasible, negotiations were undertaken with the contractor to include coated bars in contracts awarded prior to November 1978 and which included bridge deck construction in 1979 or later.

At the time the decision was made to use epoxy coated bars, no facilities for coating rebars were available in Canada. Preliminary discussions with industry representatives had, however indicated an interest in building a coating facility in Ontario. A plant specifically designed for coating reinforcing steel was designed and constructed in 1978 and

began production in early 1979. A second coating plant commenced production in 1981.

Within the Ministry, it was necessary to formulate a policy which would clearly define which bars required coating, modify U.S. specifications to be compatible with existing Ministry specifications and develop acceptance procedures for coating materials and the finished product. Plans were modified to identify coated bars by the letter "C" following the bar number and computer programs were changed to calculate the quantities of coated and uncoated bars separately. Changes were also made to bending schedules to limit the bend radius to not less than 8 bar diameters for bar sizes of 30M and less. During the winter of 1979, training courses were given to construction personnel to familiarize them with the use of epoxy coated reinforcement and acceptance requirements.

Although the bridge deck problem and the development of solutions received most attention from the task force in 1976, 1977 and 1978, it was becoming increasingly obvious at this time that other structure concrete components were vulnerable to chloride induced corrosion. Serious corrosion spalling problems to the columns and piers of major structures in Southern Ontario plus the general condition of substructure elements on many older bridges dictated the need for additional protection to parts of the bridge below the deck slab. Deterioration has been observed in substructure components where chloride contamination has occurred from surface runoff passing through leaking deck joints or poorly sited drainage pipes or by splash from adjacent roadway surfaces [18]. It is especially difficult to achieve watertight deck joints [19] and, although improvements in performance are being made, it is prudent to design abutments and piers at which joints are located with additional protection against corrosion.

A number of systems to provide the required protection to substructure elements were considered. These included:

1. Permanent Fibreglass or Plastic Forms on some elements such as columns.

2. Sealing Compounds applied to concrete surfaces.

3. Epoxy coated bars.

4. Increased concrete cover to reinforcing bars.

Since early implementation of the policy for additional protection was required, permanent forms and concrete sealants were excluded because products with demonstrated effectiveness were not immediately available. Increased concrete cover was not considered a satisfactory solution for all substructure elements due to flexural cracking under some conditions and the considerable variation in achieved cover in columns and piers reported in a 1981 Ministry investigation. Substructure elements were considered in three groups depending on the severity of exposure. For elements directly exposed to salt splash and/or roadway drainage all bars

within 100 mm of the affected surface were recommended to be epoxy coated and the class of concrete not less than 30 MPa. Requirements for the various classes of structural concrete used by the Ministry are given in Table 5. The development of a satisfactory system to fabricate coated reinforcing bars into spirals for use in circular columns was an important industry initiative that made possible the early implementation of the new Ministry policy. Elements indirectly exposed to salt, generally through windblown roadway spray were considered to be adequately protected through the use of increased concrete cover to reinforcing bars and the designation of 30 MPa concrete in place of the 20 MPa concrete sometimes specified. No additional protection was considered necessary for elements not exposed to salt such as foundation concrete and exposed substructure elements of river and rail crossings not under a joint in the bridge deck.

The proposed policy for additional substructure protection was approved by the Ministry's senior management in March 1981 and implemented immediately. Where practical, contracts already awarded were changed through negotiations with the Contractor to incorporate the additional protection.

MTC POLICIES FOR DURABLE CONSTRUCTION

In general Ministry policies concerned with the attainment of durable reinforced concrete construction have two specific objectives:

1) The prevention of freeze-thaw deterioration to the concrete, and

2) The prevention of corrosion to the reinforcing bars and the resultant spalling of the concrete cover.

The required protection is attained through the use of bituminous waterproofing membranes on horizontal surfaces such as deck slabs, the use of a class of concrete which is relatively impermeable, the specification of a cover depth which will significantly delay the time when chlorides penetrate the concrete to the depth of the steel and the provision of epoxy coated steel bars, which will not corrode, in selected areas. There are of course other requirements which are essential for the attainment of long term durability in reinforced concrete elements, not discussed in this report, such as proper air entrainment in the hardened concrete, concrete aggregates resistant to freezing and thawing and deleterious reaction with the alkalies in portland cement, and the provision of adequate drainage to minimize the ingress of water borne salt into the various components of a bridge.

The 1982 Ministry policies are summarised in Table 6.

Fig. 5 illustrates the main design features for bridge decks and barrier walls.

Substructure components, due to the variations in the severity of exposure, are considered in three groups for the purpose of providing the required protection:

Group 1. Elements Directly Exposed to Salt Splash and/or Roadway Drainage

For the purpose of identifying which substructure elements are affected by salt splash, salt splash is considered to affect all elements or parts of elements within 10 m of the edge of the roadway or future widening, and to a height of 5 m above ground level.

Ministry policies applied to most highway underpasses and overpasses in this group result in the use of epoxy coated bars in such elements as bearing seats, ballast walls, abutments, piers, cap beams, columns and some wingwalls and retaining walls. On river and rail crossings epoxy coated bars will be used only on substructure elements beneath deck joints such as bearing seats, ballast walls, abutments and some piers, columns and cap beams.

Even though sealed joints are normally used in bridge decks leakage is common [19] and the policy for corrosion protection is based on the assumption that the joints may leak during the life of the structure exposing the structural elements beneath the joints to surface run-off.

Fig. 6 illustrates the main design features for substructure elements in this group.

Group 2. Elements Indirectly Exposed to Salt (Generally through windblown roadway spray)

Ministry policies will result, on most structures, in the use of increased concrete cover to steel and a higher class of concrete for such elements as wingwalls and retaining walls not in group 1. Epoxy coated bars are not used.

Group 3. Elements Not Exposed to Salt

Elements in this group will normally include all structure foundations, reinforced concrete sections buried or covered in earth and piers, columns and cap beams of river and rail crossings not under a joint in the bridge deck. No additional protection is provided.

The Ministry policies that have the goal of significantly improving the long term durability of new bridge construction, and include such measures as increased element thickness and epoxy coated bars represent, particularly for bridge decks, a multiple approach to protection. For example the increase in concrete cover, the use of high quality concrete, the presence of the waterproofing membranes on the deck surface and the specifying of epoxy coated bars in the top mat all serve to reduce the likelyhood of corrosion induced damage to the concrete. The "belt-and-suspenders" approach is not without its critics however, who argue that initial construction costs can be reduced while still retaining an acceptable degree of assurance of durable construction.

The general opinion within the Ministry favours a somewhat cautious approach to policies and procedures for durable bridge construction

bearing in mind the comparatively poor performance of earlier standards and procedures that appeared to promise low maintenance structures. Multiple protection is considered not only reasonable but mandatory when the overall quality of bridge construction is appraised critically. It must be recognized that under many conditions it is impractical to achieve something close to perfection in the quality and dimensions of concrete, the impermeability of a waterproofing membrane and the integrity of the epoxy coating on a reinforcing bar. The reasonableness of an approach which includes multiple protective systems can also be justified on the basis of the extreme difficulty in the partial or full replacement of a deck slab particularly when segmental or other continuous systems are used.

Recent publications in the U.K. [20] and the U.S.A. [21] indicate that other jurisdictions are now considering multiple protective systems particularly for bridge decks with high traffic volumes on critical structures exposed to deicing chemicals.

COST OF POSITIVE PROTECTION

Ministry policies to provide positive protection to structures, implemented from 1978 to 1981, increase the cost of construction. For a three span highway structure the additional costs, in terms of 1981 dollars are summarized in Table 7. The example is not the same structure used to develop the data shown in Tables 3 and 4. A highway crossing was chosen, as opposed to a railway crossing, since the former requires the use of epoxy coated bars in piers and abutments in the salt splash zone and hence would give a better indication of the maximum cost of all the additional protection provided in current policy.

In this example, the structure was built in 1981, the additional cost of epoxy coated bars, increased thickness of deck slab and barrier walls and the use of a higher class of concrete in some substructure elements, amounted to 8.5% of the value of the structure.

PRESTRESSED CONCRETE

Prestressed concrete has been extensively used in highway bridges in Ontario since the mid 1950's. Early applications were mainly in precast deck beams, the units being post tensioned and manufactured on site, or at a precast plant. The late 1950's saw the introduction of cast in place post tensioned bridge decks to the Ministry system with this type of construction widely used for the interchanges of major highways. Precast beams and post tensioned bridge decks are designed with bonded cables and the post tensioning cable ducts are grouted with a portland cement grout.

Although prestressed concrete structures in Ontario have proved relatively trouble free to date there remains concern with regard to their long term performance since corrosion damage to the cables could affect the safety and load capacity of the deck slab and beams.

There have been a number of studies of the condition of prestressed concrete structures on the Ministry system. In 1972 an investigation [22] was carried out into the effects of cracks in post tensioned concrete bridge decks on the corrosion of reinforcing steel and prestressing tendons. In this study, involving 15 structures, 150 mm diameter cores were drilled through cracks in the deck slab over the ducts at a point where the ducts were closest to the roadway surface. When ducts were located, portions of the sheath and some of the exposed grout was removed so that the cable strands could be inspected for evidence of corrosion. No corrosion of the prestressing cables was observed and with one exception the ducts examined were full of hard, sound grout. The deck slabs included in this study had exposed concrete roadway surfaces and the concrete cover to the top of the cable ducts varied between 76 and 230 mm.

More recently the condition of cables in two structures has been reported [23]. In one case, a pedestrian overpass constructed in 1962, cables removed from a replaced box beam exhibited severe corrosion, accompanied by a significant reduction in the cross-sectional area of some wires, at locations where grout did not fill the duct or was of a very poor quality. In the second case of a bridge built in 1958, and demolished due to highway realignment in 1981, cables removed from the cast in place hollow box deck slab indicated only isolated examples of slight surface corrosion on the wires. The cable ducts in this bridge deck were found to be fully grouted with a dense high quality portland cement grout.

Based on these studies current Ministry practices concerned with the attainment of long term durability in prestressed concrete include:

1. Waterproofing membrane covered with protection board and hot mix paving on prestressed concrete bridge decks. (As discussed previously this is standard practice on all concrete bridge decks).

2. Concrete cover to prestressing strand and post tensioning ducts in accordance with the Ontario Highway Bridge Design Code.[10] (An example is 75 to 95 mm cover for small diameter transverse ducts and 115 to 145 mm cover for longitudinal ducts.)

3. Emphasis in construction on proper grouting procedures and the use of a high quality grout.

QUALITY ASSURANCE IN BRIDGE CONSTRUCTION

The quality of a structure depends largely on workmanship in construction. The best of materials, technology and design practices cannot be effective unless the construction is well performed. Competent inspection and adequate testing programs are necessary throughout the progress of the work to ensure a satisfactory finished product.

The assurance of adequate quality through the prevention of construction faults, for structures, may be more difficult than in many other civil engineering works. The whole team ie. the owner, the contractor and subtrades are together for a relatively short period of time. Compared to a

high rise structure repetitive operations on bridge construction occur seldom and on many contracts the contractor is performing a different operation from day to day. There is no "ground floor" on which to sort out construction problems. In some segments of the structure, for example a post tensioned voided deck slab, huge quantities of concrete are placed in a single day around a complex arrangement of voids, cables, anchorages and reinforcement. Once the concrete production, delivery, placement and finishing operation gets underway there is understandably great pressure on the contractor's and owner's staff against making decisions that will impede or halt the work.

These factors plus the inherent variability in materials and construction processes, and the vagaries of the weather present a formidable challenge to the quality assurance program in bridge works. The historical lack of concern for quality by many segments of the construction industry compounds these difficulties.

Nonetheless, as is obvious, it is possible to build satisfactory bridges, and Ontario contractors are quite capable of meeting the demands of modern construction. It is abundantly clear though that an aggressive, efficient Ministry quality assurance system is necessary to guarantee consistent high quality work in the bridge construction program. The basis of such a system must be competent inspection and adequate testing and utilization of test information on site, to control the work and to ensure a satisfactory finished product. A total optimum quality assurance system, however, encompasses a much wider area starting with adequate construction drawings, practical specifications and acceptance criteria through to a well trained, properly organized, highly motivated owner's staff intent on accepting only materials, products and construction procedures that will assure a satisfactorily finished structure.

Although a detailed description of policies and procedures with respect to Ministry quality assurance programs are outside the scope of this paper the last decade has seen the expenditure of considerable resources into the development of a satisfactory system. Reports from two studies (24, 25) produced a basic reassessment of many long standing practices and procedures along with considerable "tuning" of some components of the system. The two studies were initiated following the identification of isolated examples of poor performance and high structure maintenance costs that were related to poor workmanship in construction.

Some of the more important recommendations of the two studies were concerned with:

1) Increasing the overall effectiveness of Ministry field inspection and supervising staff by:

   - Better opportunities for career development and the provision of a salary commensurate with the responsibility of the positions.
   - Building formal accountability into the inspection function.
   - Improved training for construction staff both in the technical and contract administration areas.
   - Producing a structure inspection manual and inspection checklists.

2) Improvement in the standard of new field test laboratories and the maintenance of existing facilities and equipment.

3) A renewed emphasis on testing programs that perform the tests at the required frequency and that all tests be performed whenever possible on the site of the work.

4) Increased use of procedures documenting violation of terms of the contract by the contractor that could lead to an adjustment in his qualification rating.

5) The implementation of a policy requiring that manufacturers, suppliers and contractors be responsible for a program of process control covering the inspection and testing of their product.

6) The development of an improved attitude in the Ministry construction hierarchy that specifications, plans and other contractural documents are something more than guidelines. Such documents must be the basis of acceptance of the work.

Current new Ministry initiatives to improve the quality assurance system in bridge construction centre around the development and implementation of statistically based performance type specifications for properties of the plastic and hardened concrete and the achieved cover to reinforcing steel. Specification principles, include:

- The establishment of realistic, attainable requirements for materials and construction.
- The establishment of clear acceptance procedures including price adjustments, where applicable, for borderline quality work.
- Procedures to reduce unforseen problems.
- Prompt decisions to the contractor concerning acceptability or otherwise of materials and construction.
- Sufficient controls to obtain a satisfactory product from the worst qualified, least cooperative contractor.

Performance type specifications require the contractor and supplier to set realistic targets for material properties and construction processes to assure a high degree of confidence that the specified quality is being provided and the provision of skilled personnel who recognize conditions necessary for good results and apply corrective measures to keep the process "in control".

CONCLUSIONS

Since the rehabilitation of deteriorated structures on a highway network is expensive, technically difficult and in many cases highly inconvenient to the road user, the logical approach is to make every effort to construct bridges that have the characteristics of long life and low maintenance costs.

The developments reported in this paper, adopted by Ontario in recent years, give room for some optimism as to the long term durability of new construction. They do not however, leave room for complacency. Modern technology has not produced the magic ingredient to guarantee deterioration-free structures. The development of procedures and policies covering the design, construction and maintenance of structures that will give increased assurance of low lifetime maintenance costs must continue.

Besides the obvious needs to continue research and development in the broad area of increased durability for reinforced and prestressed concrete accompanied by realistic testing and evaluation of promising products and processes, a most important activity is the monitoring of structure performance to determine the actual benefits of design and construction improvements.

Solutions to specific issues are also required such as the attainment of watertight deck expansion joints and a methodology to guarantee protection of prestressing cables against corrosion.

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APPENDIX A - MINISTRY SPECIFICATIONS

MTC Form 1213	Material Specification for Hot Applied Rubberized Asphalt Waterproofing Membrane
MTC Form 914	Construction Specification for Bridge Deck Waterproofing
MTC Form 1150	Material Specification for Hot Mix, Hot Laid Asphaltic Concrete
MTC Form 310	Construction Specification for Hot Mix, Hot Laid Asphaltic Concrete
MTC Form 1350	Material Specification for Concrete (Materials and Production)
MTC Form 904	Construction Specification for Concrete Structures
MTC Form 905	Specification for Concrete Reinforcement
MTC Form 1443	Material Specification for Organic Coatings for Steel Reinforcement (Concrete)
MTC Form 1442	Material Specification for Epoxy Coated Steel Reinforcement (Concrete)

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Part II - Findings of the Field Observation Teams
Part III- A Study of Quality Assurance Test Programs.

TABLE 1: Achieved Concrete Cover Survey of Bridge Decks

Structure	Measured Cover		
	<51 mm %	≥51 mm %	Range, mm
14-338B	82	18	32-64
14-337	80	20	28-64
13-195	0	100	57-95
19-515	5	95	41-70+
34-212A	75	25	10-76
34-212B	35	65	32-76
36-234	9	91	38-76
37-1017	33	67	28-73*
37-1022A	2	98	41-98*
37-1022B	1	99	48-83*
27-211	37	63	32-86
27-206	30	70	35-73
7-5	4	96	48-70

+ Steel was securely tied to main beams

* Overall height of stirrups reduced in the field

TABLE 2: Anticipated Life of Epoxy Coated Bar Combinations

Type of Coating		Amount of Damage to Epoxy, %	Predicted Service Life, years
Top Mat	Bottom Mat		
Uncoated	Uncoated		5
Epoxy	Uncoated	Within specification limits	130
Epoxy	Epoxy	Within specification limits	449
Epoxy	Uncoated	0.24	138
Epoxy	Uncoated	0.86	38
Epoxy	Epoxy	0.86 (both mats)	341

TABLE 3: Initial Construction Costs for a 3 Span Highway Structure

Item	Cost $	Cost $ per sq. meter of deck slab	% of Total Cost
Foundations	57,090	68.35	21.9
Substructure	45,400	54.36	17.4
Beams	73,900	88.48	28.3
Concrete Deck Slab	75,340	90.20	28.8
Membrane, protection board and hot mix	9,529	11.41	3.6
Total	261,259	312.80	100.0

TABLE 4: Unit Costs of Various Deck Slab Construction Strategies

Alternative	Cost, $ per sq. metre of Deck Area (1976 data)				
	Initial Cost	Maintenance Costs			40 Year Lifetime Cost Assuming 10% Interest Rate
		After 15 Years	After 20 Years	After 30 Years	
1. 190 mm deck, waterproof and pave (as built)	312.80	16.79		16.79	317.44
2. 180 mm deck, 50 mm concrete overlay	325.30		3.23		325.73
3. 180 mm deck, epoxy bars, 50 mm concrete overlay	332.08		3.23		332.51
4. 190 mm deck, epoxy bars, waterproof and pave	319.59	16.79		16.79	324.22
5. 180 mm deck, 50 mm latex modified concrete overlay	326.91		3.23		327.34
6. 190 mm deck, waterproof and pave	293.65	16.79		16.79	298.28
7. 180 mm deck, 50 mm concrete overlay	305.81		3.23		306.24
8. 180 mm deck, epoxy bars, 50 mm concrete overlay	311.19		3.23		311.63
9. 190 mm deck, epoxy bars, waterproof and pave	299.03	16.79		16.79	303.66

Alternatives 1 to 5 are construction costs based on deck steel tonnage as built.

Alternatives 6 to 9 are construction costs based on deck steel tonnage in accordance with the requirements of the OHBDC.

TABLE 5: Quality Requirements for Various Classes of Concrete

Class of Concrete MPa *	Minimum Cement Content kg/m^3	Typical w/c Ratio
20	310	0.50
30	355	0.45
35	415	0.40

Note: All concrete is air entrained and contains a water reducing chemical admixture.

* Minimum 28 day Strength.

TABLE 6: Protection Requirements for Various Structure Components

Structure Component	Minimum Concrete Thickness mm	Minimum Class of Concrete MPa	Reinforcing Steel to be Epoxy Coated	Concrete Cover to Steel mm.	Other Requirements
Deck	225	30 (Reinforced) 35 (Post Tensioned)	Top Mat	70±20 (Top Mat) 40±10 (Bottom Mat)	All decks covered with hot applied rubbarized asphalt waterproofing membrane, protection board and 80 mm hot mix.
Barrier Wall	200 (Top of Wall)	30	All bars	70±20	
Substructure Components					
Group 1-Elements Directly Exposed to Salt Splash and/or Roadway Drainage	-	30	All bars within 100 mm of Exposed face	80±20 (Exposed face)	
Group 2-Elements Indirectly Exposed to Salt.	-	30	None	95±20 (Exposed face)	
Group 3-Elements Not Exposed to Salt.	-	20	None	In accordance with OHBDC	

TABLE 7: Cost of Positive Protection to a 3 Span Highway Structure (1981 Dollars)

Element	Item	Quantity	Cost $
Barrier Walls	Coating of Reinforcement	2.5 tonnes	1,895
	Wider Wall (200 mm).	10.7 m^3	3,735
Deck Slab	Coating of Reinforcement in Top Mat.	19.1 tonnes	14,740
	Thicker Slab (225 mm).	23.7 m^3	9,380
Substructure Components	Coating of Reinforcement in Columns, Cap Beams, Bearing Seats, Ballast Walls & Abutments	11.7 tonnes	9,000
	Use of 30 MPa Concrete in Columns, Ballast Walls, Abutments, Wingwalls & Retaining Walls.	28.3 m^3	710

Total Additional Cost $39,460

Value of Structure $463,400

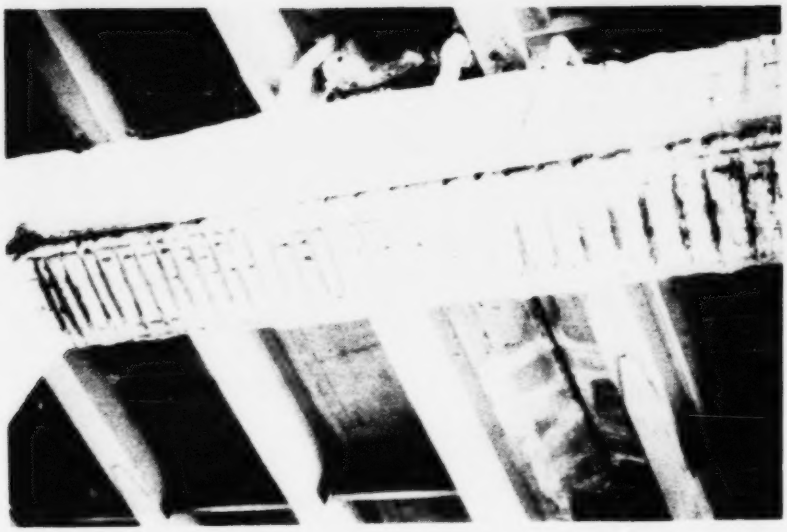
Additional Cost of Positive Protection 8.5%

1a - Concrete Deterioration to an Older Deck Slab, Southern Ontario

1b - Corrosion Spalling to a Newer Deck Slab, Northern Ontario

Fig. 1 Deterioration of Highway Structures

1c - Beam Deterioration



1d - Substructure Deterioration

Fig. 1 Deterioration of Highway Structures

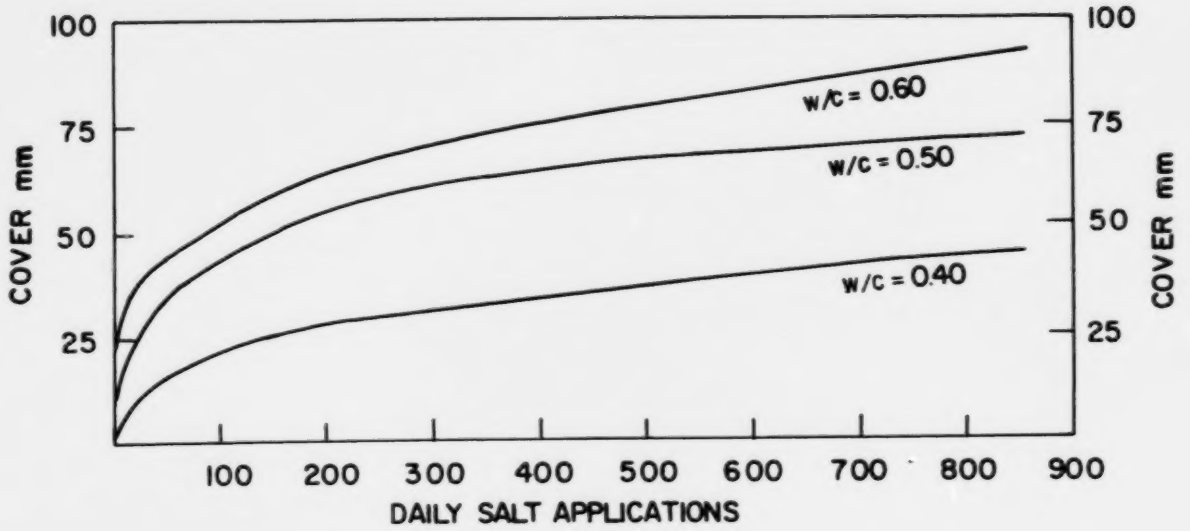


FIG. 2. EFFECT OF WATER-CEMENT RATIO AND DEPTH OF COVER ON RELATIVE TIME TO CORROSION.

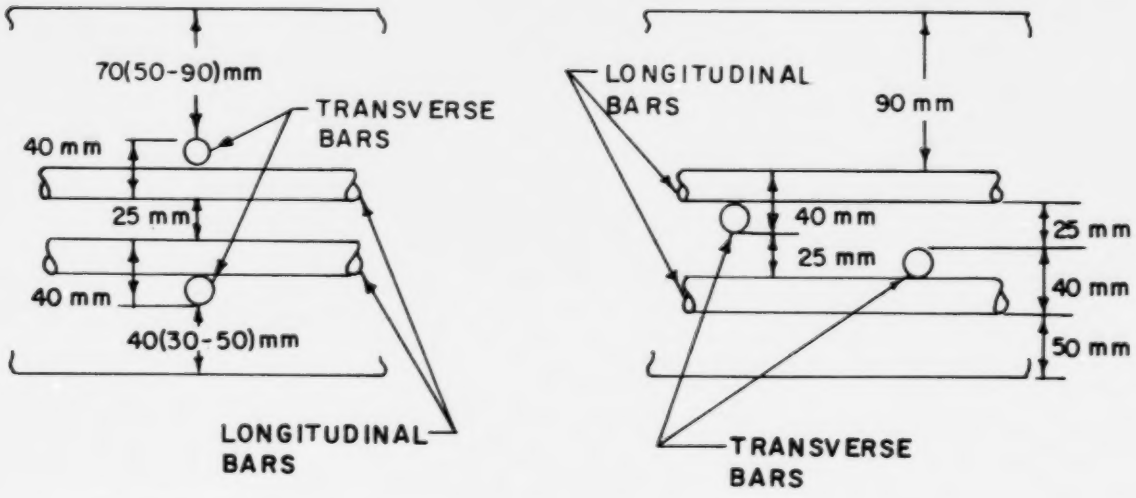


FIGURE 3. TOLERANCES FOR LOCATION OF REINFORCING STEEL IN THIN-SLAB BRIDGE DECKS.

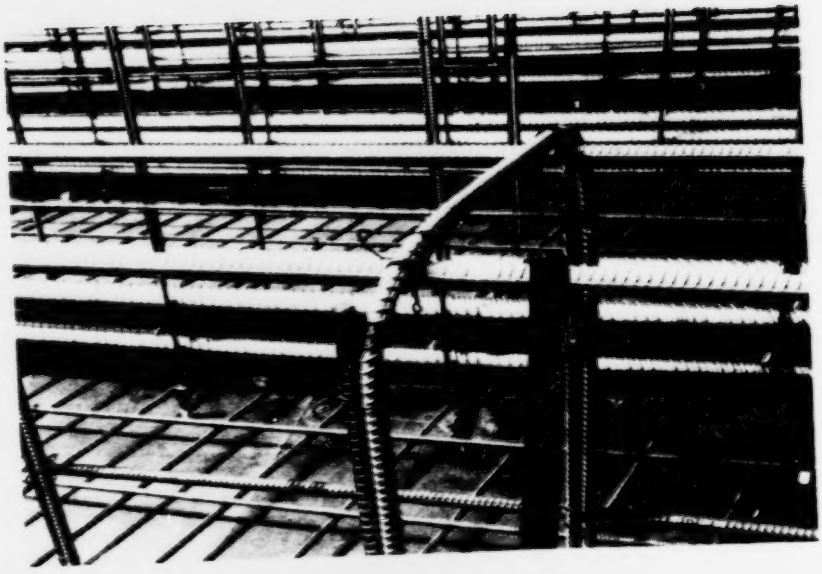
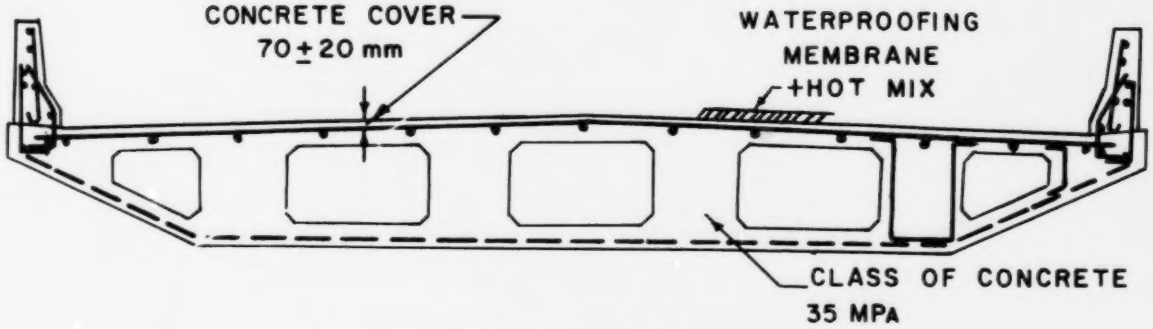
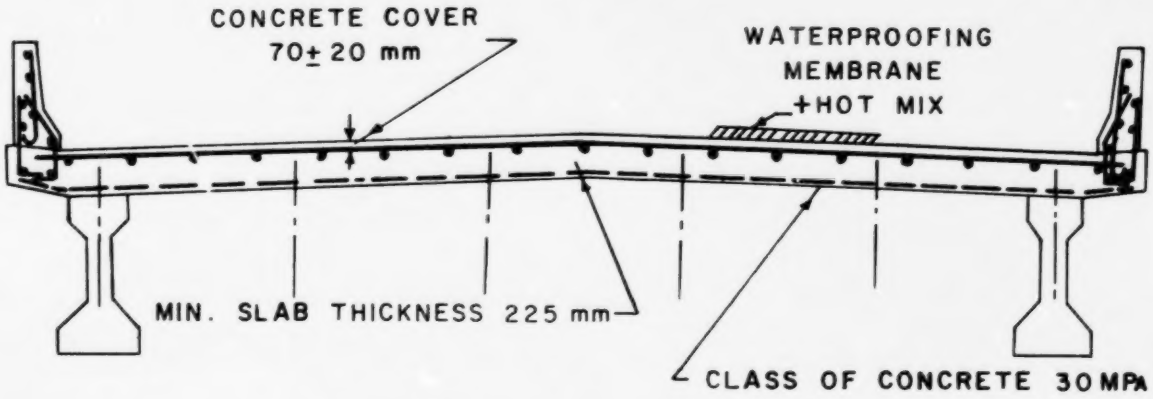


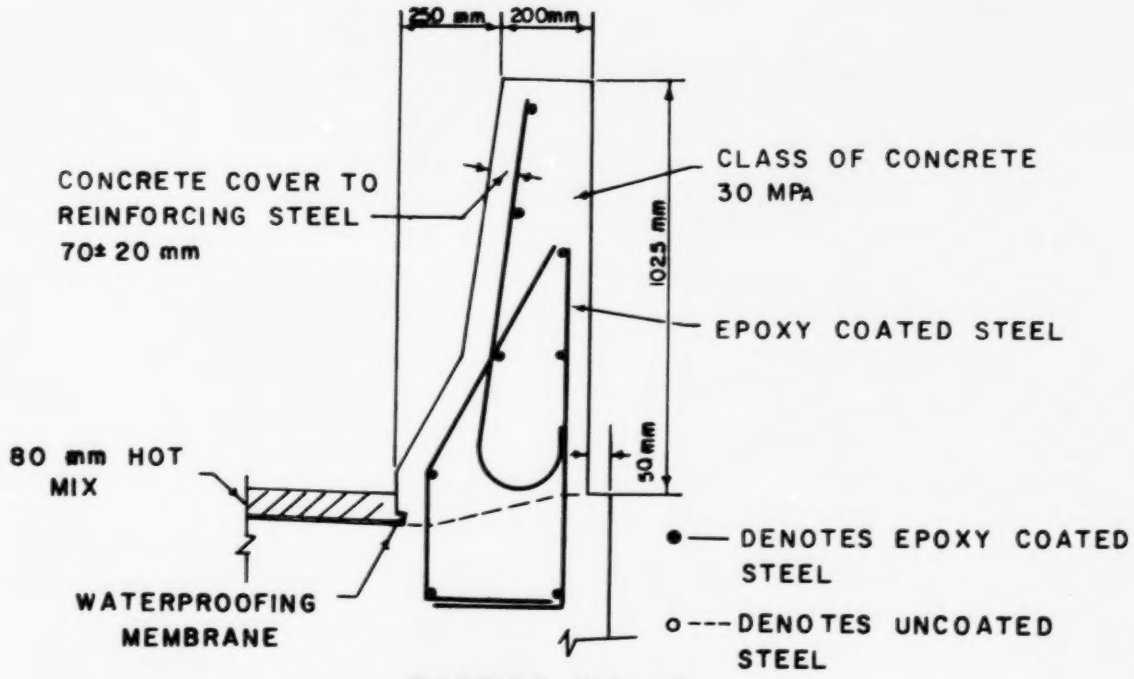
Fig. 4 Epoxy Coated Reinforcing Steel for Bridge Deck Construction



POST TENSIONED DECK

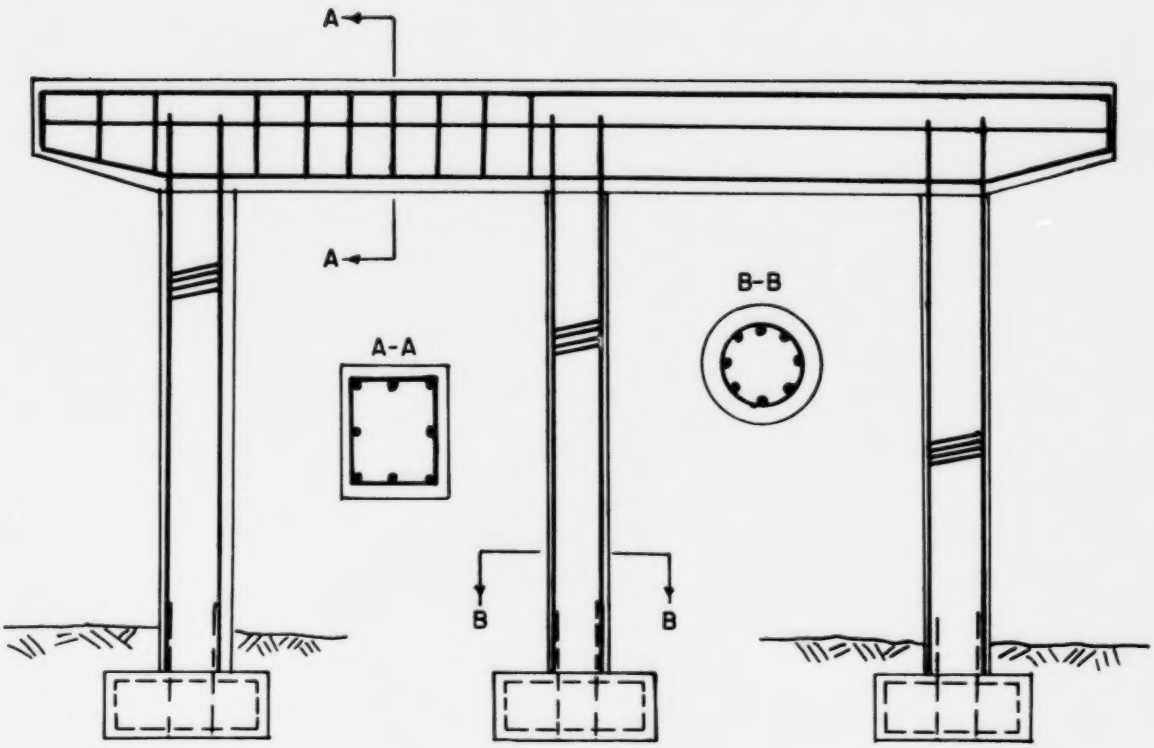


THIN SLAB DECK ON BEAMS



BARRIER WALLS

FIG. 5 DESIGN DETAILS OF BRIDGE DECKS & BARRIER WALLS



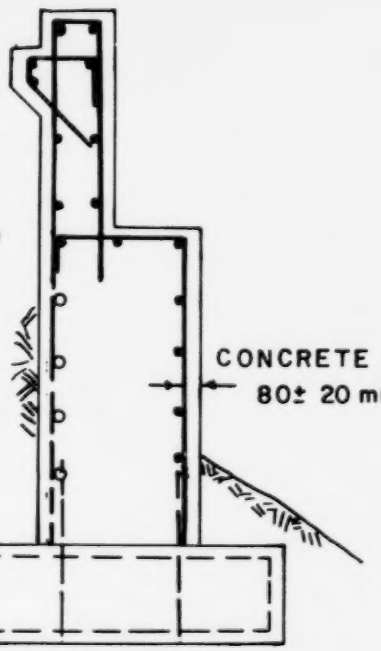
PIER COLUMNS & PIER CAPS

NOTE: 1) CLASS OF CONCRETE 30 MPa MIN.

2) CONCRETE COVER TO REINFORCING STEEL 80± 20 mm

● — DENOTES EPOXY COATED BARS

o --- DENOTES UNCOATED BARS



ABUTMENTS

FIG. 6 DESIGN DETAILS OF SUBSTRUCTURE ELEMENTS — GROUP I ELEMENTS DIRECTLY EXPOSED TO SALT SPLASH AND/OR ROADWAY DRAINAGE.